04TB-127

All-Season Virtual Test Site for a Real-Time Vehicle Simulator

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ABSTRACT

A virtual, all-season test site for use in real-time vehicle simulators and mobility models was constructed of an Army firing range in Northern Vermont. The virtual terrain will mimic the terrain of our Virtual Data Acquisition and Test Site (VDATS) at Ethan Allen Firing Range (EAFR). The objective is to realistically simulate on- and off-road vehicle performance in all weather conditions for training and vehicle design for the US Army. To this end, several spatial datasets were needed to accurately map the terrain and estimate the state-of-the-ground and terrain strength at different times of the year. The terrain strength is characterized by terramechanics properties used in algorithms to calculate the forces at the vehicle-terrain interface. The performance of the real vehicles will be compared to the simulated vehicle performance of operator-in-the-loop and unmanned vehicles for validation of the simulations. Real vehicles are instrumented and perform maneuvers at the test site to develop and validate mathematic models describing vehicle behavior in all-season conditions, including snow, ice, frozen and thawing ground.

INTRODUCTION

All-season capabilities are lacking in nearly all modeling and simulation efforts for the Army, even though on much of the world's landmass, "winter" happens every year! Although all-season vehicle performance algorithms have been included in the NATO Reference Mobility Model (NRMM II) since 1995 [1,2], and in research grade vehicle models since the late 1990s [3], these have only recently been included in the Army's wargaming simulations [4]. To advance the state of the Army's simulations, four Army research organizations joined forces in Army Science and Technology Objective (STO) #IV.GC.2003.01, "High Fidelity Ground Platform and Terrain Modeling (HGTM)". The HGTM STO aims to remedy this technology gap through a joint program among the U.S. Army Corps of Engineers research labs (Geotechnical and Structures Laboratory, GSL, and Cold Regions Research and Engineering Laboratory, CRREL), the U.S. Army RDECOM's Tank and Automotive Research and Development Center (TARDEC), and the Army Research Laboratories (ARL).

The objective of the joint research program is to make significant advances in the state-of-the-art for off-road, all-season ground vehicle models, terrain mechanics, and vehicle–terrain interaction models. This effort includes three different levels of fidelity—"high-resolution," "real-time," and "hyper-real-time," with some consistency among them [5]. The primary modeling and simulation technologies addressed include real-time simulation methods and vehicle–terrain interaction modeling, in addition to the development of standard vehicle interfaces, modeling of advanced suspension components, modeling of unconventional powertrain configurations, flexible-body dynamics models, and the modeling of virtual terrain. Of these, the real-time vehicle simulator serves as the showcase to demonstrate and evaluate the new simulation and vehicle technologies (see Figure 1). The work presented here specifically addresses the technology gap for incorporating terrain effects into real-time vehicle simulators, for all weather conditions. To do this, a virtual test terrain was constructed

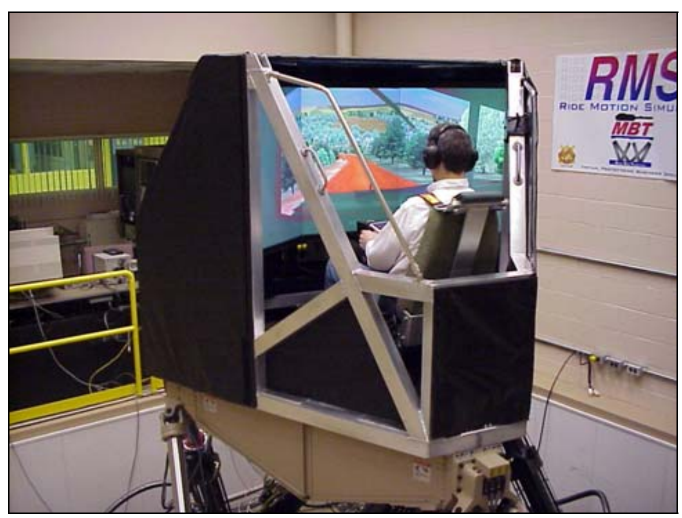

Figure 1: The Ride Motion Simulator at RDECOM-TARDEC's Ground Vehicle Simulation Lab (GVSL)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
18 AUG 2004	**journal article**	**18-08-2004 to 18-08-2004**

4. TITLE AND SUBTITLE
ALL-SEASON VIRTUAL TEST SITE FOR A REAL-TIME VEHICLE SIMULATOR

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Alex Reid; Sally Shoop; Barry Coutermarsh

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC ,6501 E.11 Mile Rd,Warren,MI,48397-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
#14230

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#14230

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Co-Authored with, Cold Regions Reserach and Enginering Laboratory (CRREL)

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**11**	

where weather extremes on the terrain are realistic and can be validated in a natural environment.

The Cold Regions Research and Engineering Laboratory, in Hanover, NH, the US Army Tank and Automotive Research, Development and Engineering Center (TARDEC) in Warren, MI, and the Vermont National Guard, in Colchester, VT collaborated to build a virtual All-Season Terrain for use in real-time vehicle simulators and Army mobility models. The virtual terrain will mimic the terrain of our Virtual Data Acquisition and Test Site (VDATS) at the Ethan Allen Firing Range (EAFR), where real vehicles perform maneuvers and data is collected to help develop mathematical models used to describe vehicle behavior in all-season conditions, including snow, ice, frozen and thawing ground. The objective is to realistically simulate on- and off-road vehicle performance in all weather conditions for training and vehicle design for the US Army.

Realistic terrain representation is the key to successful physics-based simulations of all-terrain, all-season vehicle performance. Terrain surface models include visual representations, elevation profiles and terrain features as well as terramechanical properties, soil types and the state of the ground (wet, dry, frosted, thawed, snow or ice covered) that affect mobility. These terrain and soil types must be correlated to the visual representation of the terrain using texture maps (i.e., a snowy surface must have a texture map that visually represents the snowy surface). A methodology to incorporate terrain deformation and the consequent forces on the wheel or track attributable to a variable terrain surface has also been developed [6,7]. An all-season virtual terrain has been developed with the capabilities to spatially distribute soil and snow properties and to change these to reflect seasonal changes in the terrain. The test terrain is the EAFR in northern Vermont, which consists of a wide range of terrains (mountains and valleys, forests, and fields) and soil types (see Figure 2). The real-time driver simulator will be validated against actual vehicle maneuvers using instrumented test vehicles performing the same maneuvers at this site.

Terrain mechanics modeling and simulation technologies addressed by the TARDEC–USACE project include the development of:

- Methods to generate high-resolution terrain from lower resolution databases and statistical descriptions of the terrain.
- Three-dimensional, all-season (soil, snow, ice) terrain mechanics models, including surface deformation, moisture, and temperature effects along with the generation of tractive forces.
- Obstacle layers capable of accommodating high-resolution obstacle negation experiments.
- Dynamic terrain models that allow for soil deformation memory and obstacles that change because of natural and man-made events.

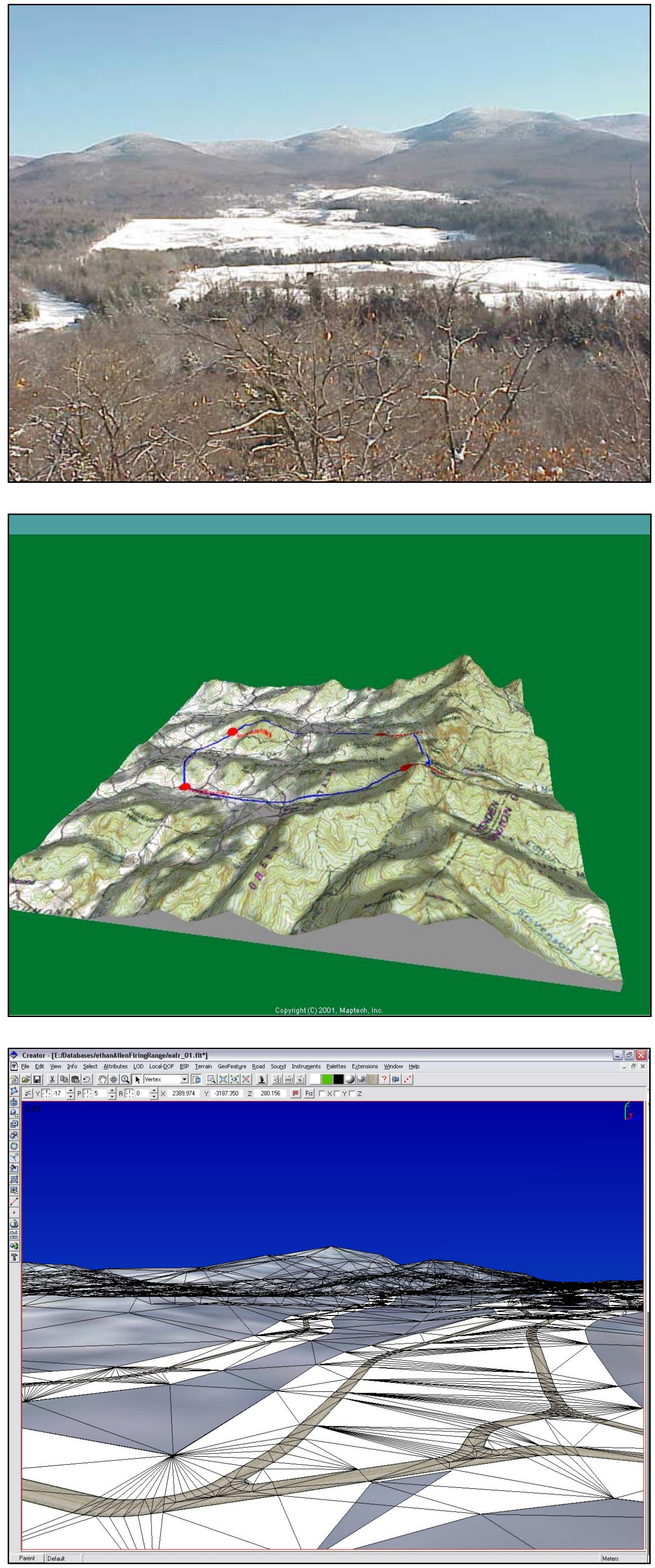

Figure 2: Real and Virtual All-Season Terrain for Ride Motion Simulator

VIRTUAL ALL-SEASON TERRAIN – ETHAN ALLEN FIRING RANGE TEST SITE

To implement and demonstrate the technology developed for all-season off-road vehicle performance, a test site experiencing a range of terrain and seasonal conditions was needed. Existing virtual proving ground capabilities do not include snow or other typical winter conditions, thus both a virtual test site and a real test site with true all-season capabilities was needed. For our purposes, EAFR located in Jericho, VT was chosen.

A primary reason for this choice in a test site is that although the initial demonstration will mimic the EAFR site, the site covers a wide range of environmental conditions and terrain possibilities, which will make the methodology developed applicable to most other terrains. EAFR lies in the northern Green Mountains of Vermont, extending from a low elevation of about 200 m near Jericho Center, to 958 m at Mt. Mayo, near Bolton Mountain and on the southern edge of Mt. Mansfield. The large change of elevations within the reservation provide a wide range of weather conditions, from Burlington, VT, at an elevation of about 40 m near Lake Champlain, to the summit of Mt. Mansfield at 1307 m. Desirable characteristics of the site include; extremely varied topography and vegetation ranging from mountainous (forested and/or bare rock) to open fields, a 46.5 sq. km area with various climatic and seasonal conditions, a close proximity to CRREL for moving test vehicles and personnel, a vast network of off-road, trails and roads and good accessibility and availability for research testing. The climate is a moist, humid continental climate very similar to that found in central Europe (Germany and former Eastern Block nations), the Low Countries of Europe, southern Scandinavia, northern Italy, northern Yugoslavia, eastern Russia, Korea, and eastern China. Vegetation varies from eastern hardwood deciduous species at lower elevations, to mixed deciduous-coniferous, and near complete coniferous at the highest locations. Average soil frost depths are approximately 127 cm, with extremes of 152 or more cm. Rime icing is common above 792 m elevation, especially on west facing slopes. Weather conditions at Barre, VT, at an elevation of 353 m, give some indication of conditions in EAFR, Table 1.

One of the key activities at EAFR is The Mountain Warfare School run by the Vermont Army National Guard. This mountain school trains soldiers in cold-weather operations, specifically mountain mobility. Training covers both summer and winter training for operations in mountainous environments, such as Afghanistan, and includes many students from the Special Forces or Rangers. The winter training teaches students how to use adverse weather and terrain conditions to their advantage, and how to operate in mountainous conditions under all climatic conditions [8]. This makes the site ideal for assisting the Army in building its simulation capabilities for all-season conditions.

SPATIAL DATA COMPONENTS

Several spatial datasets were obtained with the assistance of the State of Vermont Military Department to build the virtual terrain. These include a 30 m grid DEM (Digital Elevation Model) from the US Geological Survey (USGS), engineering soil type and soil drainage information derived from the National Resource Conservation Service (NRCS) soil maps, vegetation types derived from forest classifications and Digital Ortho-Quad (DOQ) imagery of the area, Global Positioning System (GPS) positioning of roads and trails, aerial and ground photography for texture mapping in the visualization, and in limited areas, LIDAR data to create a high-resolution (20 points per square meter) DEM. All of these were incorporated into the virtual terrain to simulate the VDATS terrain features and behavior, including the influence of the soils and snow on vehicle traction and maneuvers.

Table 1. Typical weather characteristics expected near the test site in Northern Vermont (temperature in °C, precipitation and snow in cm).

Month	Average High	Average Low	Warmest on record	Coldest on Record	Average Precipitation	Average Snowfall
JAN.	–3	–13	19	–36	6.6	58.9
FEB.	–1	–13	14	–32	7.1	64.0
MARCH	3	–8	25	–28	6.6	41.7
APRIL	11	–1	28	–17	6.6	12.2
MAY	18	5	31	–6	7.6	0
JUNE	23	11	33	–2	7.6	0
JULY	26	13	36	–1	7.4	0
AUG.	24	11	34	–1	8.6	0
SEPT.	20	7	33	–7	7.9	0
OCT.	14	2	29	–9	7.9	1.5
NOV.	7	–3	24	–22	7.9	17.0
DEC.	–1	–11	16	–31	6.6	42.7

The DEM for the entire site, in Figure 2, illustrates the relatively flat to rolling hills of the western portion of the test area gradually increasing to the steep slopes and high elevations of the eastern portion of the test area which lies just west of Mt. Mansfield, the highest peak in Vermont. The mountainous peaks lie above the tree line and occur just east of the test area. Slope aspects are predominately westward. Soils are primarily silts (over 60%) with clayey sands common on the eastern portion of the test site consisting of the western slope of the Green Mountains of Vermont (Figure 3). Sands predominate in the lowlands and outwash areas.

One of the major trail networks, accessible for small and lightweight vehicles, is an old biathlon range on Feigel hill. This trail network was mapped by the VT National Guard using GPS on an All Terrain Vehicle (ATV) and are shown in red in Figure 4. This network is a prime location for off-road vehicle traverses, particularly for lightweight or robotic reconnaissance vehicles.

A two square kilometer area of the site was included in a high-resolution LIDAR survey in 2002. The outline of the LIDAR data collection is shown in Figure 4. The resulting LIDAR DEM is based on approximately 20 ground elevation points per square meter. The high-resolution elevations will be used for a terrain data subset for small, lightweight (30 kg) robotic vehicle tests and simulations, and to characterize the terrain roughness for impact on vehicle performance.

TERRAMECHANICS SURFACE

Terramechanics properties describe the terrain condition and strength for calculating the forces at the vehicle-terrain interface. In the initial version of the interface software, the algorithms are based on off-road vehicle performance algorithms based on those in the NATO Reference Mobility Model (NRMM) for snow, and based on the WES numerics for soil. [7] The Application Programmers Interface (API) for the terramechanics algorithms is generic so that the algorithm versions can be easily upgraded as they become available. The terramechanics terrain properties for version 1.0 of the terramechanics program consist of soil type, cone penetration resistance, snow depth and density, frost and thaw depth, and the presence of surface ice. These are linked to the virtual terrain using a lookup table, which will reflect different seasonal conditions. The terramechanics table potentially can be changed over time, even within the simulation run, to represent weather effects on the terrain materials.

The terrain geometry model and the Ride Motion Simulator computer generated imagery will be based on an OpenFlight® virtual terrain database. The desire is to use the OpenFlight® database to store the soil/terrain attributes required by the terramechanics model. The terrain attribute or code assigned to the real-time terrain is a code defining the soil type, drainage, combination slope and aspect classification, and vegetation index.

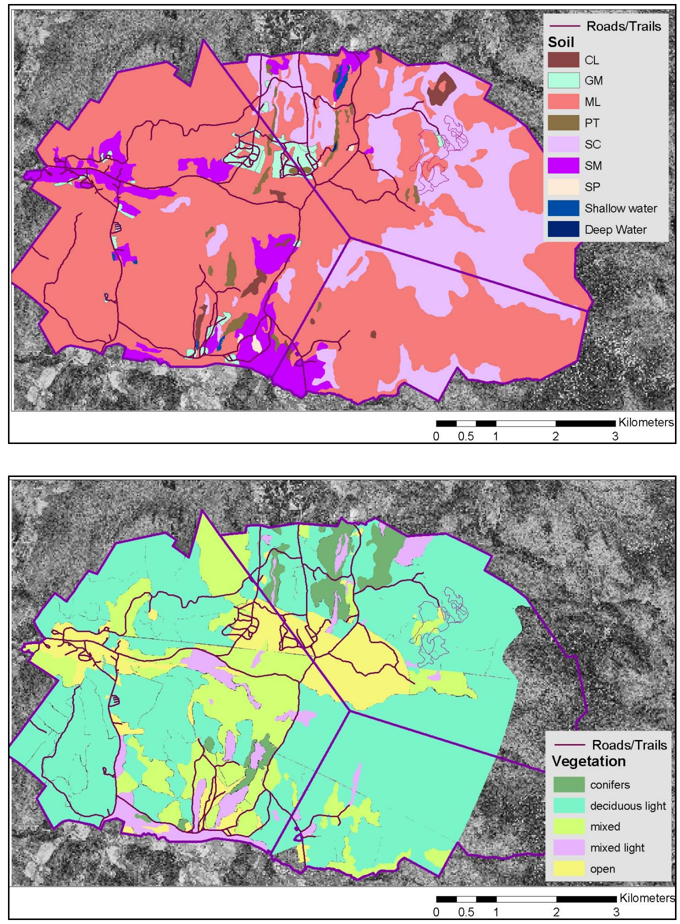

Figure 3: GIS layers defining soil class and vegetation class

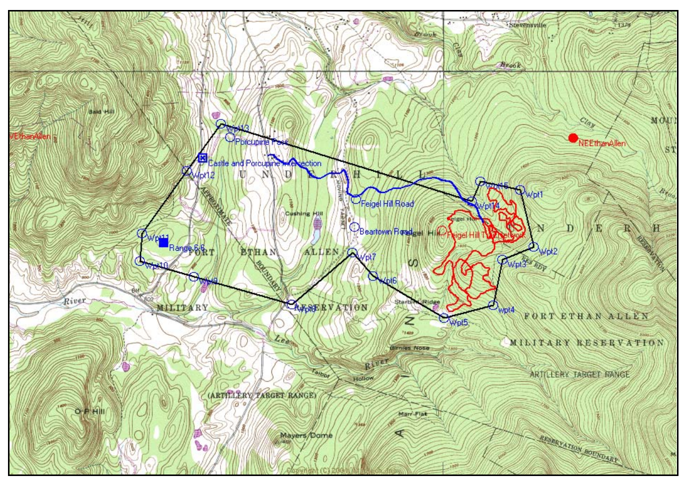

Figure 4: Old Biathlon Range on Feigel Hill at EAFR

Using these four parameters, plus elevation (which is passed back and forth during force calculations), allows us to distribute the terrain properties across the terrain based on time of year, or even time of day. The number of classes and associated bits for each parameter are

given below. Combined, this scheme results in defining the terrain properties using 16 bits, in order to minimize information needed in memory and real-time calculations. The classifications for each of these parameters are given in Tables 2, 3, and 4, and 5. The five parameters that will make up the HGTM terrain surface type are:

Soil Codes (20)	5 bits
Drainage indices (6)	3 bits
Slope and Aspect classes (27)	5 bits
Vegetation indices (6)	3 bits
Total (67200)	16 bits

For each combination of these types, there will be a lookup table that will link the codes to the correct terrain mechanics properties to run the model. We plan on using a different lookup table for each month of the year (approximately), to incorporate the seasonal aspects of the terrain surface properties. Conceptually, we could also change lookup tables during the simulation to bring in weather effects on the terrain during the simulation.

Bullock developed methodology to infer soil strength values from soil type, wetness index, geographic location and seasonal parameters.[9] Following this methodology, a combination of soil type and drainage information can be used to infer soil strength based on the time of year. This type of analysis was used to spatially and seasonally distribute terrain strength in a Geographic Information System (GIS) for off-road mobility analysis.[10] Extending this to include winter effects (snow cover and thawing/frozen ground), tables of distinct terramechanics properties based on weather conditions (e.g. monthly, daily, or seasonally) indexed to a set of principle terrain codes should allow the real-time simulator to demonstrate differences in terrain condition spatially and temporally during driven simulations. Microclimate considerations suggest that soil type, drainage, slope, aspect, and vegetation should provide a

Table 2: Soil/Surface Type Index.

Soil/ Surface Type Index	USCS Soil Type	Description
1	GW	Well graded gravel
2	GP	Poorly graded gravel
3	GM	Silty gravel?
4	GC	Clayey gravel
5	SW	Well graded sand
6	SP	Poorly graded sand
7	SM	Silty sand
8	SC	Clayey sand
9	ML	Silty clay
10	CL	Clay
11	OL	Organic clay
12	CH	Highly plastic clay
13	MH	Highly plastic silty clay
14	OH	Plastic organic clay
15	PT	Peat
16	RK	Rock
17	2RD	Secondary road
18	RD	Primary road
19	SWT	Shallow water
20	WT	Deep water

Table 3. Drainage Index categories [9]

Drainage Index	Climatic Zone	Depth to Water Table	Depth of Wetting	General Characteristics of Sites
0	Arid	Indeterminable	Less than 0.3m	Located in desert regions.
1	Dry	Indeterminable	0.3–1.2m	Steeply sloping, denuded or severely eroded and gullied.
2	Average	More than 1.2m	More than 1.2m	Well-drained soil with no restricting layers or pans; fair to good internal and external drainage. Slope may be flat to steep.
3	Wet	0.3–1.2m	To water table	Soil not well drained. Restricting layers or deep pans may be present. May occur at base of slopes, on terraces, upland flats, or bottom lands.
4	Saturated	Less than 0.3m	To water table	Sites waterlogged of flooded at least part of the year. Bottomlands subject to frequent overflow. Upland with poor drainage or shallow pans. Slopes with very poor drainage.
5	Saturated	Zero (surface)	Complete	Areas perennially waterlogged. No change in water content or soil strength.

Table 4. Solar Exposure Slope and Aspect Classes.

<table>
<tr><th>Slope</th><th colspan="10">Class</th></tr>
<tr><td>0–3</td><td colspan="10">0</td></tr>
<tr><td>3–7</td><td>1</td><td rowspan="2">5</td><td rowspan="4">7</td><td rowspan="2">8</td><td>10</td><td>14</td><td rowspan="2">18</td><td rowspan="4">20</td><td rowspan="2">21</td><td>23</td></tr>
<tr><td>7–10.5</td><td>2</td><td>11</td><td>15</td><td>24</td></tr>
<tr><td>10.5–15</td><td>3</td><td rowspan="2">6</td><td rowspan="2">9</td><td>12</td><td>16</td><td rowspan="2">19</td><td rowspan="2">22</td><td>25</td></tr>
<tr><td>≥15</td><td>4</td><td>13</td><td>17</td><td>26</td></tr>
<tr><td colspan="11">0 36 72 108 144 180 216 252 288 324 360</td></tr>
<tr><td colspan="11">Azimuth</td></tr>
</table>

Table 5. Vegetation Classes.

Index	Vegetation Category
0	Open field
1	Mixed light
2	Deciduous light
3	Deciduous dense
4	Conifers dense
5	Mixed dense

unique set of indices which when combined with climatologic and geographic information to allow estimates of terramechanics properties in the following form:

- Cone Index 0-15 cm
- Cone Index 15-30 cm
- Snow Depth
- Snow Density
- Frost Depth
- Thaw Depth

These can be pre-determined on a monthly or scenario basis, without the need to modify and recompile the OpenFlight® files. These codes were chosen to be easily convertible to other terrain data types (used in Army simulations). A complete description of the relationships between the various data structures is given in [7].

Snow properties will be distributed across the terrain based on mass and energy balance considerations (Melloh et al., in progress). Parameters considered in determining the snow depth (as well as density, snow water equivalent, strength, etc.) are elevation, solar exposure (slope and aspect), and vegetation (forest canopy effects). While elevation, and to a lesser extent forest canopy,(through interception) impact snow fall and accumulation, all these parameters affect the snow melt pattern. Elevation is available during the realtime calculations and is therefore available to distribute snowfall across the elevation and temperature gradient. During the late winter and spring, when the primary process is melt, the snow properties will be spatially adjusted using the categorical class combinations of solar exposure (more melt on south facing slopes) elevation (temperature gradients) and vegetation (sub-forest canopy energy balance). The solar exposure classes (Table 4) were chosen based on clear sky solar radiation as a function of latitude, longitude, elevation, slope and aspect (azimuth). The vegetation classes (Table 5) are used to adjust snow properties due to forest effects. These effects are reduced solar transmittance, reduced longwave radiation losses, and reduced wind speeds that moderate turbulent energy fluxes and snow interception during an accumulation phase. This is a general approach for considering elevation, solar exposure and vegetation effects on snow property distribution that is applicable to other areas of the world. Local adjustments or fine-tuning of the parameters is desirable. For example, in the application to Ethan Allen the slope categories were adjusted to fit the range and prevalence of slope categories actually present.

EAFR VIRTUAL TERRAIN VISUALIZATION

The ultimate goal for the VDATS is to develop a high-resolution, simulated, all-weather terrain that accurately reproduces the real terrain found at the EAFR. This virtual terrain is then used as the surface that physics based dynamic models of vehicles can traverse in either real-time, man-in-the-loop simulations using the six degree-of-freedom Ride Motion Simulator (RMS) at TARDEC (see Figure 1), or other high-resolution computer based analysis of vehicle performance. With this high-resolution simulated terrain skin, the simulations should come close to recreating what would occur in the field at EAFR. The VDATS will be used as a tool to develop and verify physics based algorithms to accurately model ground surface response to tires and tracks, i.e. - vehicle movements that ultimately will reproduce vehicle traction, sliding and rolling resistance along with the attendant inertial response of the vehicles. Once this surface/tires and track interaction is modeled correctly, the VDATS becomes a valuable tool for a range of uses. These include virtual vehicle/robotic

development, vehicle/robotic response and performance to changing weather, terrain and environmental conditions and driver reaction under varying weather and performance conditions.

In order to correctly enable the simulated driving experience, the driver's visualization of the virtual terrain should realistically mimic the actual terrain. This detail is important when the simulated driving experience will be used to help determine driving tactics and procedures that could be used in the real environment under conditions encountered in the simulator. TARDEC has access to three image generation computers to accomplish this task, including: an Evans & Sutherland ESIG-HD/3000® and Harmony™ and a Silicon Graphics Inc. Onyx4.

The first step in creating a virtual terrain skin is to obtain accurate (to some degree) data describing a portion of the earth of interest to the user. This data is typically in an x,y grid with corresponding elevation values. Examples of this data would be Digital Terrain Elevation Data (DTED) from the National Geospatial-Intelligence Agency (formerly NIMA) or Digital Elevation Model (DEM) data from the U.S. Geological Survey. This data is typically available in 30m resolution, sufficient for most applications, but insufficient to create a realistic and reliable virtual terrain skin.

Once the elevation data has been obtained for a region of interest, a visual terrain database must be created. This is the virtual world that the driver will navigate during testing. There are many tools used to create the virtual terrain, including MultiGen™ Creator® and TerraVista Pro™. This will create a polygonal mesh that represents the elevation data (see Figure 5). To increase the realism, objects are now added to the database. These include: structures, trees, vegetation, and finally, texture maps. The texture maps are simply photos that are overlaid upon the polygons to give a realistic appearance to the database (see Figure 6). The virtual database is now at the level that is most commonly used throughout industry, military and academia. However, for the needs of the VDATS, this resolution is not good enough.

There are two areas that need to be addressed for the virtual terrain database: increased terrain skin resolution (reduce from 30m resolution to sub-meter or better) and the incorporation of the terrain features themselves into the polygonal information. By features, we mean characteristics such as: soil type, drainage characteristics, vegetation, slope and aspect.

THE NEED FOR HIGH-RESOLUTION TERRAIN DATA

In order to be able to conduct engineering-level, man-in-the-loop simulations using the RMS or to improve the reliability and accuracy of the modeling and simulation of

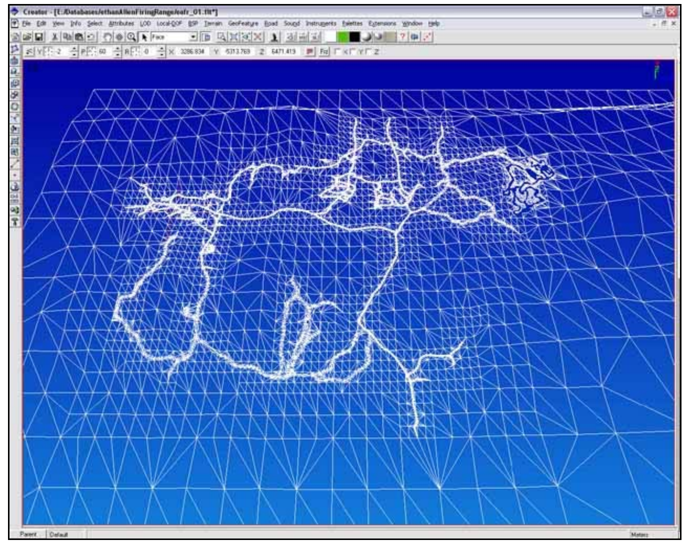

Figure 5: Polygonal Mesh of EAFR

Figure 6: Virtual Terrain compared to Actual Photos

new, existing, or prototype vehicle platforms, the terrain skin used in simulation must be improved. The real-time dynamic model is a high-fidelity, multi-body, physics based mathematical model representing the vehicle's dynamics. The Ride Motion Simulator is capable of re-creating six degree-of-freedom motions with a bandwidth approaching 40 Hz. Thus, the limiting factor in creating a truly high-resolution, engineering-level simulation is the terrain skin that is used.

The terrain skin that the real-time vehicle dynamic model traverses (which we will hereafter refer to as the real-time terrain) is typically derived from the virtual terrain that the image generator is using (we will hereafter refer to this as the visual terrain). There are pros and cons to this method. The pro is that the terrain inputs to the suspension system are the same as the terrain that the occupants are viewing and provides the proper correlated visual/motion queues. The con is that an image generator can only display a limited amount of polygons per scene. This leads to the terrain being broken up into polygons of a fairly large size, typically from 30m to 90m in size or larger. Thus, a cross-country terrain is reduced to 30m resolution, thereby removing all higher frequency ground content that would excite the vehicle during the traversal. Unfortunately for the dynamic model, this is equivalent to driving over a flat world and in no way can properly represent a cross-country terrain. In order to properly recreate the effects of off-road simulations, a higher fidelity and resolution terrain database must be used as an input to the dynamic model.

However, if the real-time terrain is vastly different from the visual terrain that the image generator will render, simulator sickness (motion sickness discussed below) may occur during a motion-based simulation. Hence, the challenge in increasing the resolution of the real-time terrain is to keep it correlated to the visual terrain.

One solution to this problem is to develop a separate, high-resolution terrain database for use as an input to the dynamic model but yet have it be correlated to the image generator's visual terrain database. This high-resolution terrain database would consist of two parts: the original image generator's terrain skin and a separate portion which consists of high-frequency, low-amplitude terrain which is simply added to the image generator's terrain skin.

CREATION OF HIGH-RESOLUTION EAFR TERRAIN SKIN (NURBS)

This section describes the development of a new methodology for creating a high-resolution surface which can be stored with as little information as possible, and which can be summed to (overlaid upon) a lower-resolution surface derived from a computer image generator's database. This technique has been integrated into the HGTM STO and is outlined here.

To create the high-resolution surface, one must know a few details about the type of terrain they wish to create. The minimum and maximum frequency content must be known. This relates to the wavelengths of the terrain surface one would wish to create. For example, the virtual surface developer may wish to create a surface with bumps/hills having wavelengths between 0.5 meters and 5 meters. The developer must also have an idea of the rms (root-mean-square, a measure of roughness) value for the terrain and an idea of the frequency distribution of the waves in the surface. Does one want more higher frequency content than lower frequency content? More lower than higher? Or a uniform distribution? This information forms the basis for the creation of NURBS (Non-Uniform Rational B-Splines) patches that will capture the higher resolution terrain characteristics and will be added to the polygonal surface. Advantages of using NURBS include easy and quick data evaluation (given some x,y value, the elevation can be quickly computed) and that it provide a continuous surface.[11]

Spectral fractal geometry (fractional Brownian motion) was used to create a high-resolution surface in the frequency domain, which was then transformed into the spatial domain using a two-dimensional inverse FFT (Fast Fourier Transform). The fractal dimension (used in fractal geometry) is used to shape the data in the frequency domain. The higher the dimension, the more emphasis is placed upon higher frequency terms. The lower the fractal dimension, the more emphasis placed upon lower frequency terms (rolling hills). Figure 7 depicts the effects on a PSD plot of a surface by varying the fractal dimension. Typical values range from 1 to 3.

Now that the minimum and maximum frequency content of the surface patch is determined, the control points describing the NURBS surface patch are then extracted so the spatial representation contains the desired frequency characteristics.

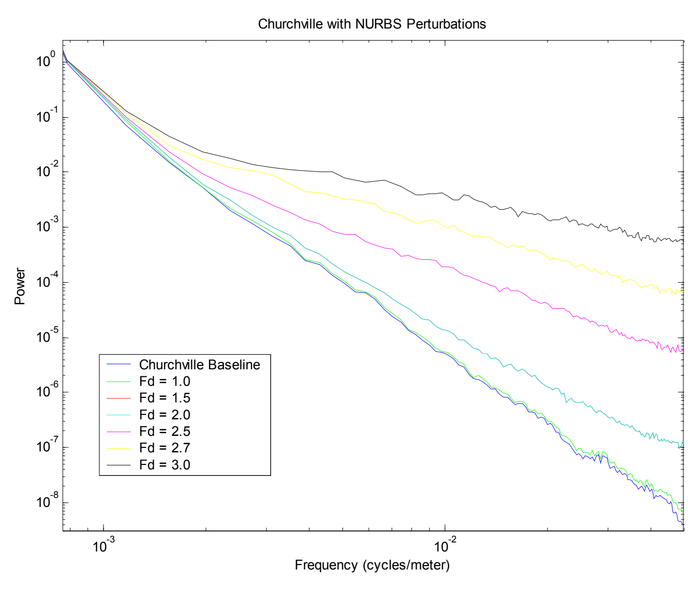

Figure 7: The Effects on a PSD by Varying Fractal Dimension

The STO team is currently developing a library of representative surface patches which can be overlaid upon the low-resolution terrain surface in real-time. This results in a geometrically smooth, high-resolution surface that is correlated to the lower resolution surface from the image generator. While a driver is navigating the image generator's database, the mathematical model representing the vehicle is receiving terrain input at a continuous resolution from the correlated high-resolution NURBS database. This unique methodology permits one to create an infinite resolution database storing a small, finite set of data points which describe the NURBS surface patches.

The development and implementation of this technology will provide a ground simulator with a high-fidelity terrain surface with user selectable frequency content, rms and frequency shaping (through the fractal dimension coefficient) for use with a real-time dynamic model that is correlated with an image generator's database. This will provide the motion simulator with realistic terrain inputs, thus creating a more realistic simulation.

VISUAL CORRELATION OF THE TERRAIN SURFACES

As mentioned above, a potential for simulator sickness arises using any method where the motion-based simulator will be traversing a different database than the occupant is seeing. When the occupant sees the terrain that he is traveling over, he is expecting to feel certain vibrations as he traverses it. If he is feeling the vibrations from a different (or in this case modified) terrain, simulator sickness may set in. This happens when his brain tells him from experience to feel one thing, but the simulator does something else. Obviously, a way to impart this new terrain information visually to the user is needed.

An Evans & Sutherland Harmony® image generator is being used is because it provides the ability to manipulate the surface normals on the rendered polygons (Phong shading). This will create variable shading throughout each individual polygon instead of one constant shade for each polygon because of the way that the light source reflects back at different angles to the user’s eye off of the polygonal surface. This technique is called bump-map texturing. This lends the illusion of being able to render more image content than a typical image generator. Figure 8 depicts an image of the EAFR using Phong shading and bump-mapped texturing.

VALIDATION

Also important is the simulated terrain’s ability to mimic the environmental conditions found in the real environment that affect vehicle performance. This is important for mission planning realism where seasonal changing environmental conditions affect vehicle mobility. Illustrative examples are surface thawing of frozen ground in the spring months or snow retention on certain terrain regions that would make mobility difficult.

To accurately describe these features in the simulated terrain, the detailed soil, vegetation, drainage and elevation data, mentioned previously has been collected. Terrain aspect, vegetation, elevation and weather conditions will be used to predict soil moisture and snow retention which affects traction and defines expected go/no-go areas accurately keyed to time-of-year scenarios. CRREL has done research on snow depth predictions and is applying that knowledge to the VDATS simulated terrain. Fieldwork to verify and refine the predictions is ongoing as part of our VDATS development Figure 9.

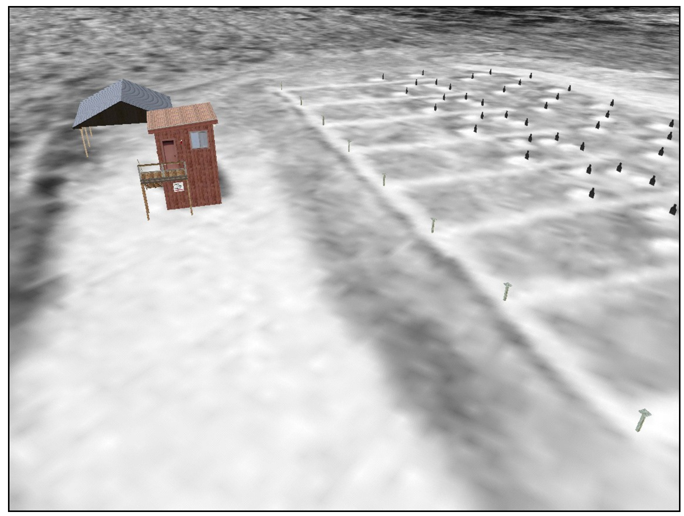

Figure 8: EAFR Winter Scene Rendered on the Harmony®

Figure 9: Obtaining Snow Parameters at EAFR

The CRREL Instrumented Vehicle (CIV) is a fully instrumented test vehicle capable of numerous measurements that can be used to characterize the vehicle's response to various terrain inputs. It has three-axis load cells at each tire to measure vertical, longitudinal and transverse wheel forces, a 10-Hz GPS system, and a six-axis Motion Pak to measure vertical, longitudinal and transverse accelerations along with yaw, pitch and roll rates.

As part of our verification in the RMS simulation development, a series of comparative tests are planned between the RMS mathematical models and the CIV. These tests will be performed to determine the CIV measurement resolution on certain terrain features, to characterize the CIV response over resolvable terrain features and to verify the RMS mathematical model of the CIV on the resolvable features. The exact form these comparative tests will take is still in the planning stages but concepts are presented below.

Baseline data to determine the CIV measurement system's resolution will be gathered by reproducing some standard acceleration, braking and lane change maneuvers as well as by traversing easily reproducible “bumps” over a range of speeds. The tests will start with single small-height bumps to determine the resolution of the different CIV sensors as well as to delineate data interpretation procedures that will be meaningful for our comparative tests. Larger and more complex features such as trapezoidal bumps and depressions will be added as necessary to determine sensor response across a broad spectrum of objects.

Once the baseline data collection and interpretation is complete the CIV will traverse certain controlled areas representing various terrain surface types in the VDATS to compare its measured responses to the RMS algorithms in those same areas. These surface types will include gravel-surfaced roads; both well graded and poorly graded, grass-covered off-road trails, tracked trails and grass cover. This will be done at representative times of the year when surface trafficability is substantially affected by environmental conditions, e.g. in a summer condition, a winter snowfall condition and a wet surface (mud) condition to enable a check on the physics based algorithms for the surface traction. Responses to be compared will include wheel forces, vehicle center of gravity (c.g.) movement, steering angle and throttle inputs at various points on the terrain. Also obtainable are accelerations at various points around the vehicle such as wheels, axles, and frame, with the addition of auxiliary accelerometers.

At the conclusion of the initial verification the VDATS and RMS can be used to validate several different vehicle simulations including existing models of HMMWV's, and robotic vehicles (Figure 10). A portable data acquisition system has been acquired to allow us to instrument vehicles with the GPS, and Motion Pak sensors along with recording any inherent sensors that each vehicle might have or wish to add.

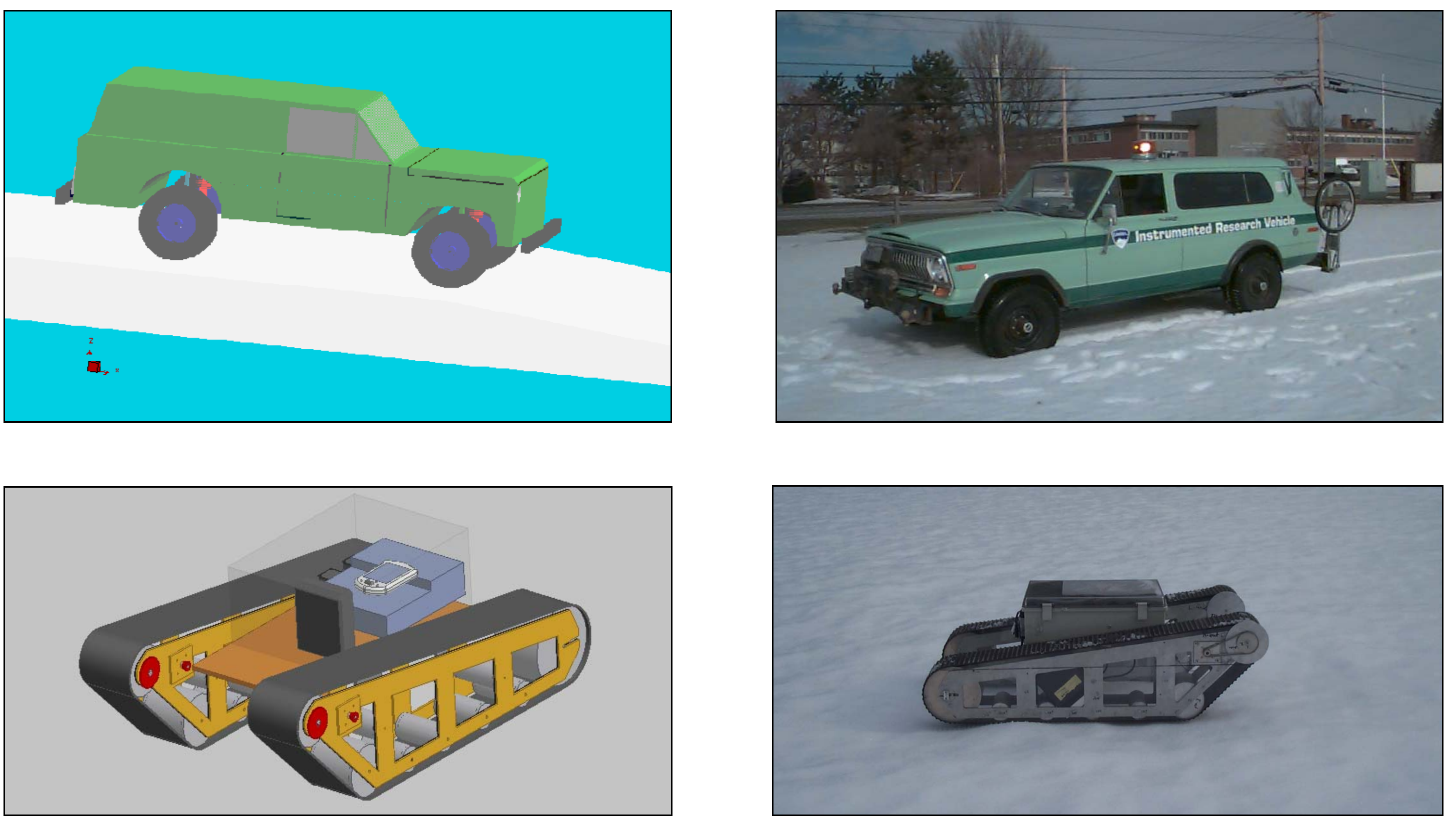

Figure 10. The CRREL Instrumented Vehicle (CIV) accurately measures tire forces at the surface interface and was simulated for use in the CRREL tire model validation. Also shown is a real and modeled robotic vehicle.

CONCLUSIONS

A joint program between the U.S. Army Corps of Engineers research labs (GSL and CRREL), the Tank and Automotive Research and Development Center (TARDEC) serves to advance the vehicle–terrain modeling and simulation capabilities for “high-resolution,” “real-time,” and “hyper-real-time.” An all-season virtual terrain has been developed with the capabilities to spatially distributed soil and snow properties and an interface to incorporate terrain deformation and the consequent forces on the wheel or track on variable strength terrain surface was developed. These modeling efforts represent a significant step forward in our ability to accurately simulate all-season vehicle performance in a real-time simulator.

ACKNOWLEDGMENTS

The authors acknowledge the many other team participants contributing to this program. The work was developed under the STO management team lead by Pat Nunez and Mark Brudnak of NAC-RDECOM. Rosa Affleck of CRREL assisted in the GIS analysis. Paul Richmond (CRREL) led the team assembling the methodology for the terramechanics codes. Rae Melloh (CRREL) developed the scheme for realistically distributing the snow depth across the virtual terrain. Chuck Ryerson (CRREL) assembled the meteorological data for the Ethan Allen Firing Range.

Shawn Allen and Corey Bruce of the University of Iowa assisted in visual data collection and assembling the virtual test site.

Mike O’Hara, State of Vermont Military Department, has provided GPS and terrain information about EAFR and MSgt. Neil Sargent of the Vermont National Guard has provided invaluable assistance and support at EAFR.

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